Possible Super-Enhanced Emission of Gravitons in Atomic Gases

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Abstract

We propose a novel mechanism for the super-enhanced emission of gravitons in an atomic gas, driven by laser fields. This enhancement originates from a collective multiphoton-multiatom absorption process, which is intrinsically coupled to the simultaneous emission of a graviton from the multiatom system. Crucially and naturally, the graviton emission process is postulated to operate independently of competing photon emission channels, ensuring that its rate can can achieve a near-saturated, substantial level.

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The experimental investigation of gravitons, the quantum carriers of gravitational interactions, remains one of the most elusive challenges in fundamental physics due to their exceptionally weak interaction with matter. While numerous proposals have been put forth for graviton detection [1–6], our recent work introduces a novel approach to tackle this challenge through a super-enhancement mechanism that leverages multiphoton-multiatom (MPMA) processes within an atomic gas [7]. This method significantly amplifies the otherwise negligible absorption of gravitons in the optical frequency range [8–14], and is readily realizable without requiring advancements in current technology.

Building on this enhancement mechanism, a logical next step is to investigate whether a similar process could facilitate the emission of gravitons. We contend that this is indeed plausible and that an experimental test can be implemented with relative ease. Achieving graviton emission would not only provide a laboratory source of gravitons for fundamental studies but also open up new technological possibilities, such as graviton-mediated telecommunication. Such a technology could penetrate any material and function in all environments, as the likelihood of graviton absorption along its path is virtually negligible.

The MPMA process [15–19] is a simultaneous high-order quantum electrodynamics phenomenon that can be naturally extended to encompass the absorption of a graviton by an m-atom system (m is an integer larger than one). In this collective excitation process, a single atom of species A in the m-atom system absorbs a graviton, while each of the remaining $m-1$ atoms—belonging to a different atomic species B—simultaneously absorbs a photon from a laser field (see Fig. 1 for an example with $m = 3$). This cooperative absorption becomes possible through an appropriate selection of atomic species and laser frequencies, ensuring that energy conservation is satisfied jointly by the entire m-atom system. At the same time, energy conservation is not fulfilled for the independent absorption of a graviton or a photon by a single atom. The energy conservation condition governing this joint process is given by:

$$\hbar\Omega_g + (m-1)\hbar\Omega_{\mathfrak{L}} = \hbar\omega_a + (m-1)\hbar\omega_b \tag{1}$$

where $\hbar$ is the Planck constant, Ω_g and $\Omega_{\mathfrak{L}}$ denote the (angular) frequencies of the graviton and the laser photon, respectively, while ω_a and ω_b represent the transition frequencies of the A-species and B-species atoms, respectively. Additionally, $\Omega_{\mathfrak{L}}$ must be significantly detuned from ω_b, for instance, by around 100 τ_B , where τ_B is the natural width of the relevant excited state of a B-species atom. This detuning prevents direct single-atom excitation via

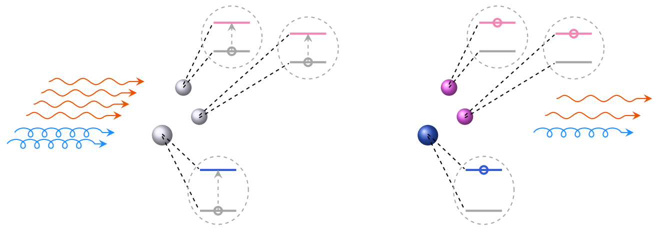

FIG. 1. Schematic plot of a graviton-absorption atomic process involving simultaneous joint excitations of a three-atom system. The A-species atom (represented by the large ball) absorbs a graviton (curly line), while each of two B-species atoms absorbs a laser photon (wavy line).

laser photon absorption alone, ensuring that excitation occurs only through the collective mechanism.

By employing this simultaneous MPMA process, we can substantially enhance the graviton absorption rate in a dense atomic gas composed of A-species and B-species atoms, where a vast number of m-atom systems are subject to the graviton-absorption transition in parallel. The enhancement factor is related to the combinatorial number $C_{m-1}^{N_{\mathfrak{bo}}} \approx N_{\mathfrak{bo}}^{m-1}/(m-1)!$, where $N_{\mathfrak{bo}}$ is approximately the number of B-species atoms within a volume defined by a linear size of l_{mpma}, a characteristic length associated with the MPMA process [18, 19]. By appropriately selecting the laser frequency and atomic species, l_{mpma} can reach values as large as 1.0 mm while $N_{\mathfrak{bo}}$ can exceed 10^{12} or more. Consequently, the absorption rate can be significantly boosted to an observable level, overcoming the inherently weak coupling between the graviton field and atomic matter.

One might then wonder whether this collective enhancement mechanism can also be utilized to amplify graviton emission from atoms. The key point is that such atomic graviton emission must be intrinsically linked to an MPMA process, forming a single, inseparable quantum phenomenon. In this scenario, neither the graviton-emission subprocess nor the MPMA subprocess can exist independently; this condition is guaranteed by enforcing energy conservation, which is satisfied only when both subprocesses are combined into a complete process.

Indeed, such a composite process arises naturally and can be interpreted as a generalized MPMA process that incorporates the intrinsic emission of a bosonic particle, such as a photon or a graviton. To illustrate, consider first an m-atom system exposed to two laser

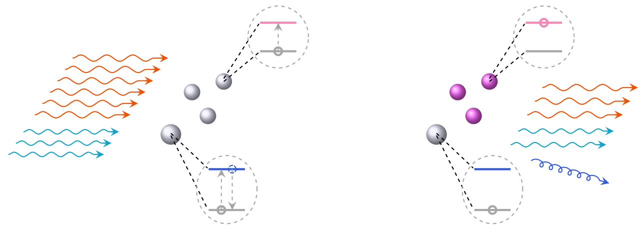

FIG. 2. Schematic illustration of a four-photon-one-graviton-four-atom process. The A-species atom (represented by the large ball) absorbs a $\mathfrak{L}_1$ photon (green wavy line) and emits a graviton (curly line),while each of the three B-species atoms absorbs a $\mathfrak{L}_2$ photon (red wavy line).

fields with frequencies $\Omega_{\mathfrak{L}_1}$ and $\Omega_{\mathfrak{L}_2}$. If these frequencies satisfy the resonant condition:

$$\hbar\Omega_{\mathfrak{L}_1} + (m-1)\hbar\Omega_{\mathfrak{L}_2} = \hbar\omega_a + (m-1)\hbar\omega_b, \tag{2}$$

the m-atom system can undergo joint excitation, with the A-species atom absorbing a photon of frequency $\Omega_{\mathfrak{L}_1}$ and each of the $m-1$ B-species atoms absorbing a photon of frequency $\Omega_{\mathfrak{L}_2}$. This describes the conventional MPMA process. However, if the laser frequencies are tuned such that Eq. (2) is not satisfied—for instance, if $\Omega_{\mathfrak{L}_1}+(m-1)\Omega_{\mathfrak{L}_2}-\omega_a-(m-1)\omega_b = \delta_\Omega$, where δ_Ω is a non-zero detuning on the order of τ_B—the system cannot achieve exact joint excitation of all m atoms to their excited states. Instead, it can undergo an alternative joint process involving virtual excitations of some atoms. For example, all $m-1$ B-species atoms may each absorb a laser photon of frequency $\Omega_{\mathfrak{L}_2}$, while the A-species atom absorbs a photon of frequency $\Omega_{\mathfrak{L}_1}$, undergoing a virtual excitation and simultaneously transitioning back to the ground state by emitting a graviton with frequency: $\omega_a+\delta_\Omega = \Omega_{\mathfrak{L}_1}+(m-1)\Omega_{\mathfrak{L}_2}-(m-1)\omega_b$. This process constitutes an m-photon-one-graviton-m-atom phenomenon (see Fig. 2 for an example with $m = 4$).

In essence, this process is somewhat analogous to photon scattering by an atom in a laser field with a frequency that is non-resonant with the atom's transition frequency. In such cases, the atom cannot absorb the laser photon directly but can scatter it through a virtual transition process, whereby the laser photon is absorbed and simultaneously a photon with the same frequency is emitted. Similarly, the m-photon-one-graviton-m-atom process involves the inelastic scattering of a laser photon into a graviton in a collective manner, with the emitted graviton having a frequency determined by the energy conservation of the entire process. Since this frequency differs from that of a scattered photon, the emission of a graviton becomes an integral and inseparable part of this generalized MPMA process.

In a dense atomic gas with a large number of atoms, the emission rate of a graviton in an m-photon–one-graviton–m-atom process can be substantially amplified due to the vast combinatorial number of possible m-atom systems that can form from the large atomic population. However, this m-photon–one-graviton–m-atom process is generally accompanied by another competing mechanism in which the emitted graviton is replaced by a photon of the same frequency. This alternative process, referred to as an $(m+1)$-photon–m-atom process, involves the emission of an additional photon instead of a graviton.

For an isolated m-atom system, the $(m+1)$-photon–m-atom process would completely dominate over the m-photon–one-graviton–m-atom process, since the coupling of a graviton to an atom is many orders of magnitude weaker than that of a photon. A crucial question then arises: in a dense atomic gas, does the m-photon–one-graviton–m-atom process remain overshadowed by the $(m+1)$-photon–m-atom process to the same degree, potentially leading to a nearly complete suppression of the graviton-emission rate? The analysis of this issue hinges on the characteristic length l_{mpma} associated with each MPMA process [18, 19]. We have argued that in a dense atomic gas, the transition rate of each MPMA could reach a near-saturation regime [19], where l_{mpma} self-adjusts so that the transition rate (per each A-species atom) W_{a_o} in the atomic gas remains below c/l_{mpma} where c is the speed of light. The restriction $W_{a_o} \leq c/l_{mpma}$ follows the general principle of relativistic causality, which states that no physical event can propagate faster than the speed of light [19].

We assume that both m-photon-one-graviton-m-atom process and the $(m+1)$-photon-m-atom process are independent quantum processes, each with its own characteristic length l_{mpma}. The photon-only process typically has a smaller l_{mpma} to reach its near-saturation rate, while the m-photon-one-graviton-m-atom process requires a larger l_{mpma}. In the near-saturation regime, the transition rate is proportional to c/l_{mpma}. Consequently, the emission rate of gravitons (per each A-species atom) [26], although potentially one or two orders of magnitude lower than the photon emission rate, can still reach a value of 10^4 Hz or higher under realistic conditions. The emitted gravitons can then be detected by a nearby atomic gas, where their absorption triggers photon emission at characteristic frequencies (see Fig. 3). It is also worth noting that the emission of higher multipole photons in an atomic gas can be achieved in a similar manner.

Given that a graviton carries two units of angular momentum, the conservation of angular momentum in the generalized MPMA process raises a potential challenge: graviton

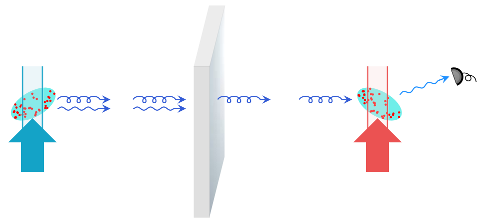

FIG. 3. Gravitons emitted by the left atom gas under laser excitation (with only one laser depicted) travel to the right atom gas, where they can be detected. A metal barrier is positioned between the two gases to block the photon transmission.

emission might appear prohibited. This is because the virtual excitation of an A-species atom, achieved by absorbing a laser photon, typically involves a dipole transition with a change of angular momentum by one unit. In contrast, the subsequent virtual de-excitation accompanied by graviton emission requires a change of two units of angular momentum, creating an apparent mismatch.

This issue can be addressed using two possible approaches: i) Higher Energy Level Transition: The target excitation level of the A-species atom is chosen such that it can decay to an intermediate level (distinct from the ground state) via a transition carrying two units of angular momentum, enabling graviton emission while conserving angular momentum. ii) Laser Photons with Two Units of Angular Momentum: The laser field supplies photons with two units of angular momentum, allowing the A-species atom to undergo a virtual electric quadrupole ($E2$) transition to an excited state, followed by graviton emission back to the ground state. Although $E2$ transitions are generally weaker than dipole transitions, the significant enhancement factor provided by the MPMA process can compensate for this weakness, making observable graviton emission feasible.

It is noteworthy that in MPMA processes, the conservation laws for energy and momentum/angular momentum are applied in fundamentally distinct ways. Energy conservation functions as a collective principle, requiring that the total energy of all participating particles—atoms, photons, and, when involved, gravitons— remains conserved between the initial and final states. However, this principle does not apply to individual atom transition event during the absorption or emission of photons or gravitons. This collective approach of energy conservation is essential for preserving the coherence and indivisibility of the MPMA quantum process. In contrast, the conservation of momentum and angular momentum is

applied at the individual level, governing the specific interactions of each atom with a photon or graviton. Here, we assume that physical interactions among the atoms are negligible.

Alternative systems for the emission of gravitons include ion-doped crystals, which may offer advantages over atomic gases in several respects, similar to their use in graviton detection [7]. The doped ions—particularly rare-earth elements such as Eu^{3+}, Nd^{3+}, and Pr^{3+}—possess unoccupied, localized quantum states, enabling them to act as photon-absorption sites, similar to atoms in a gas. A multiphoton-multiparticle process capable of graviton emission, also referred to as a generalized MPMA process, can be established in these crystals, where an m-ion system takes on the role of an m-atom system [27]. Unlike atomic gases, these ions can achieve significantly higher densities with relative ease. Even at a modest doping rate of 10 ppm, ion densities can reach 10^{18} ions/cm^3. Such a low doping rate is preferable for reducing the inhomogeneous linewith broadening of the ions' optical transitions, denoted by τ_{inh}. Studies have demonstrated that τ_{inh} can be reduced to a few hundred MHz in certain crystal systems [28–31]. Another notable property of rare-earth ion optical transitions is their exceptionally narrow natural linewidths, τ_{ion}, often on the order of 10 kHz or lower.

Due to inhomogeneous broadening, not all m-ion systems within a length scale l_{mpma} contribute effectively, as their excitation energies exhibit a spread of approximately $m\hbar\tau_{inh}$ or less. This may introduce a reduction factor in the formal expression of the graviton emission rate, roughly about $\tau_{ion}/m\tau_{inh}$ or less, Nevertheless, this reduction can be easily outweighed by the vast combinatorial number of possible m-ion systems that can form within a large ion population. As a result, the graviton-emission process can still approach a near-saturation regime, in which l_{mpma} self-adjusts to regulate what would otherwise be an unphysically large emission rate.

In summary, we propose a mechanism for super-enhanced graviton emission through a generalized MPMA process. The experimental implementation is straightforward, and the development of a laboratory-based graviton source holds significant promise for advancing both fundamental research and technological innovation.

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[26] The graviton emission rate refers to the total emission rate, accounting for all possible quantum states of the graviton. It is the sum of the exclusive emission rates corresponding to each distinct quantum state. The same interpretation applies to the photon emission rate in the $(m+1)$-photon–m-atom process.

[27] It can be noted that, all ions in the m-ion system can be of the same type; however, the target excitation level of one ion differs from that of the remaining $m-1$ ions, while the target excitation level is identical for those $m-1$ ions.

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